

# Gaseous Hydrogen and Muon Accelerators

Rolland Johnson,  
Muons, Inc., Batavia, IL

Muons, Inc. has formed partnerships with IIT, Fermilab, Jefferson Lab, and EM Design, LLC and obtained funding through the DOE SBIR/STTR program to develop techniques for muon beam cooling. Three funded projects are to develop

- 1) high-pressure high-gradient RF cavities,
- 2) cryogenic pulse compressors for high-power cavities, and
- 3) six-dimensional beam cooling using a helical dipole magnetic channel and continuous gaseous hydrogen absorber.

# Muons, Inc. (est. 2002)

- July 2002
  - High-Pressure RF Cavities
    - STTR Ph I grant with IIT-DK (\$100k/9mos)
- July 2003
  - High Pressure RF Cavities
    - STTR Ph II grant with IIT-DK (\$500k/2yrs)
  - Cryogenic Pulse Compressors
    - Joint Venture with EM Design LLC
    - STTR Ph I grant with Fermilab-DF (\$100k/9mos)
  - 6-d Helical Dipole Cooling Channel
    - SBIR Ph I grant with Jlab-YaD (\$100k/9mos)

# Need for Cooled Muon Beams

- Muon Colliders (Energy Frontier Machine)
  - Not limited by synchrotron radiation like  $e^+e^-$
  - 1/10 energy and footprint of Proton Colliders
- Neutrino Factories (Muon Storage Ring)
  - Exciting New Physics
- Intense Sources of Muons
  - e.g. Muon Spin Resonance

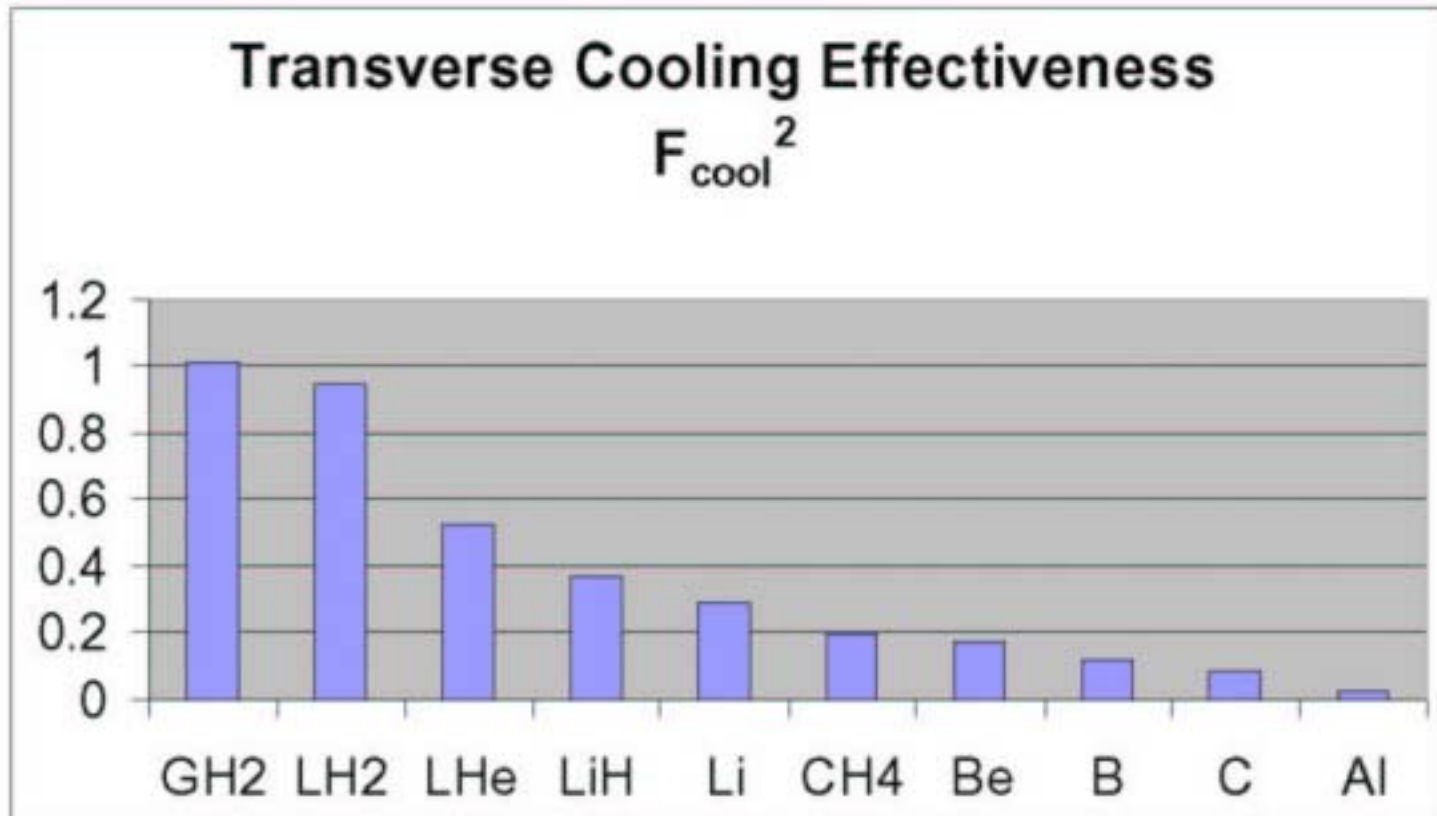
# Muon Ionization Cooling

- Muons lose energy by  $dE/dx$  in 3 directions
- Longitudinal energy replaced by RF
- Focused by 5 Tesla solenoidal field
  - No Superconducting RF
- Cools to limit of multiple scattering

# Hydrogen Gas Virtues/Problems

- Best ionization-cooling material
  - $(X_0 * dE/dx)^2$  is figure of merit
- Good breakdown suppression
- High heat capacity
  - Cools Beryllium RF windows
- Scares people
  - But much like  $\text{CH}_4$

# Comparison of Absorber Materials



# Regions of Interest for High Pressure Gaseous Hydrogen Cooling Channels

	Pressure	Temperature	$\rho/\rho_{\text{LH}}$	$dE/dx$	$L/200\text{M eV}$	$V_s$	$R_s/R_{s293}$	$R_s/R_{s293}$
	Atm	K		MeV/m	m	MeV/m	(@ 200MHz)	(@ 800MHz)
Gaseous H <sub>2</sub>								
atSTP	1	293	0.001	0.04	5304	4	1.00	
Felici[1948]	23	293	0.027	0.87	231	28	1.00	
Lab G achieved	12	77	0.054	1.72	116	50		
Lab G goal	100	77	0.450	14.35	14	435	0.35	0.35
Liquid H <sub>2</sub>								
Averages Double Flip	1	293	0.125	3.98	50	50	1.00	1.00

# HP HV RF Cavities

- Dense  $\text{GH}_2$  suppresses high-voltage breakdown
  - Small MFP inhibits avalanches (**Paschen's Law**)
- Gas acts as an energy absorber
  - Needed for ionization cooling
- Only works for muons
  - No strong interaction scattering like protons
  - More massive than electrons so no showers



# 2002 STTR Phase I Project

To build an RF test cell for testing breakdown characteristics of gases for ionization cooling.

For use in Phase II for the exploration of Paschen's Law, relating breakdown voltages to gas density, over a range of temperatures, pressures, external magnetic fields, and ionizing particle radiation at Lab G and the Linac Test Area.

# Gaseous Hydrogen for Muon Beam Cooling

R. P. Johnson, R. E. Hartline  
*Muons, Inc., Batavia, IL 60510*

C. M. Ankenbrandt, M. Kuchnir, A. Moretti, M. Popovic  
*Fermi National Accelerator Lab., Batavia, IL 60510*

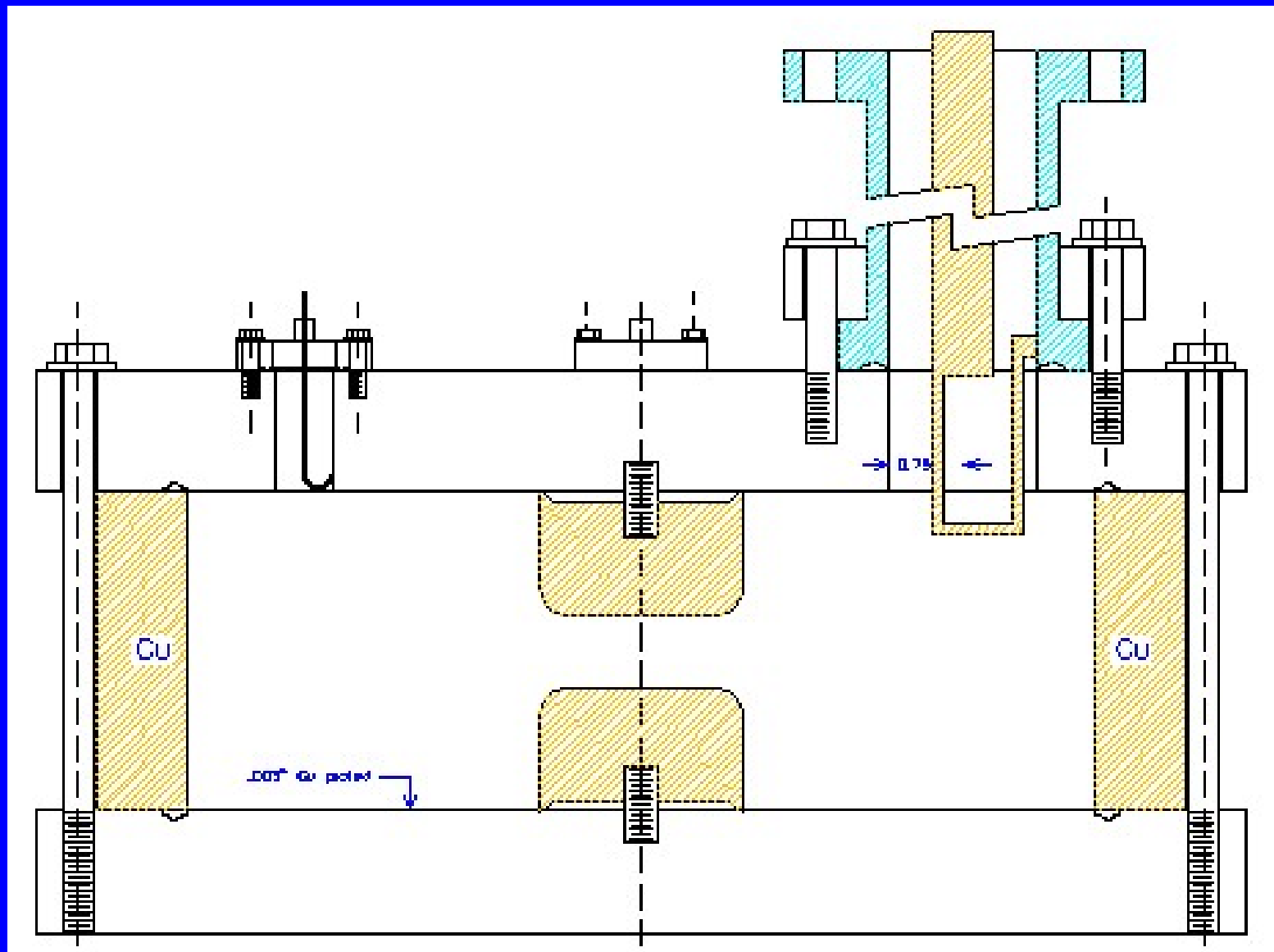
M. Alsharo'a, E. L. Black, D. M. Kaplan,  
*Illinois Institute of Technology, Chicago, IL 60616*

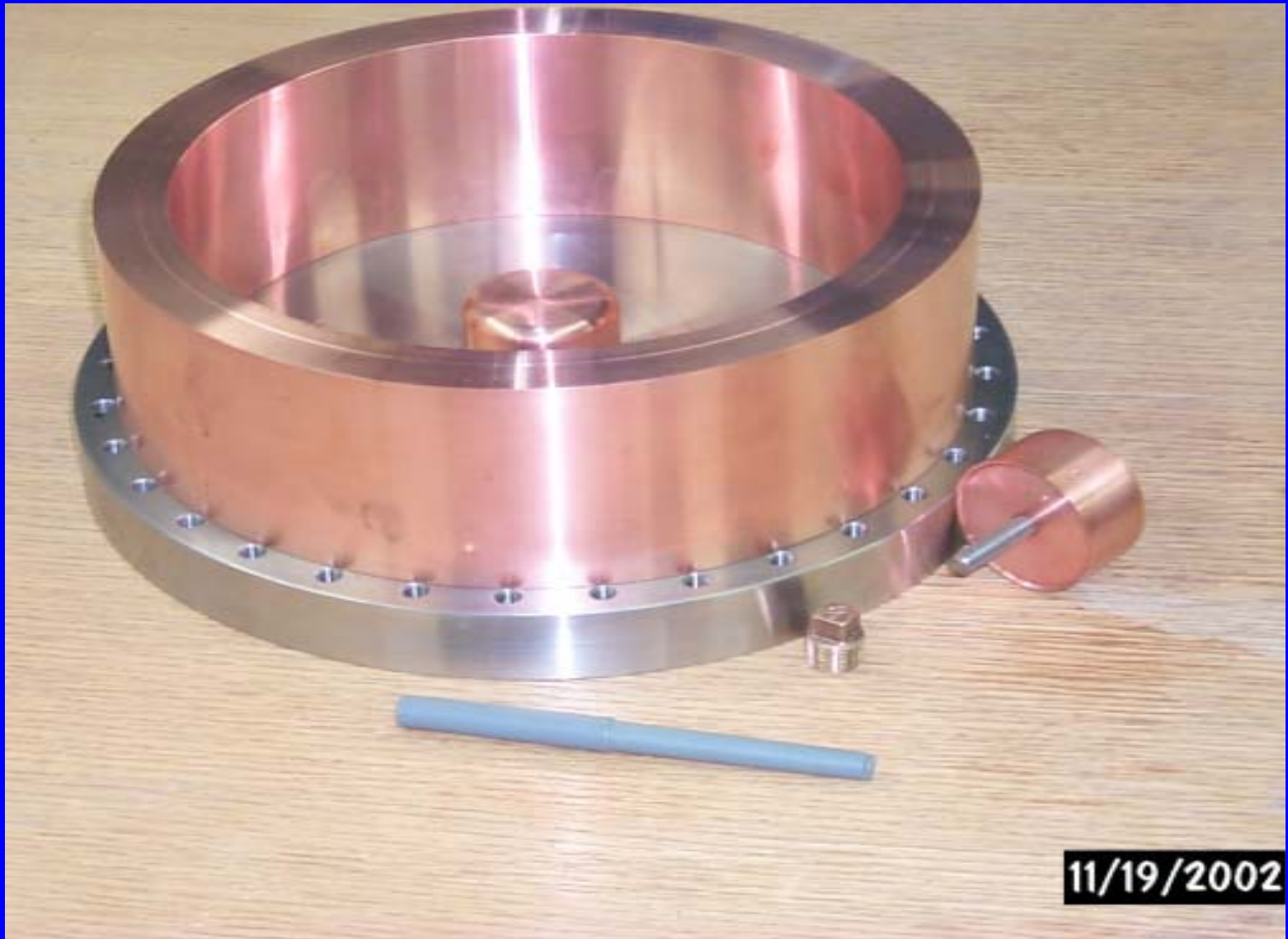
phase I results presented at PAC2003  
Paper available at <http://members.aol.com/muonsinc>

# Special Acknowledgements

- John Anderson
- Wes Smart's Committee, esp. Jim Kilmer and Tom Peterson
- Cary Kendziora, Del Allspach, Jim Tweed, Sauli Sylejmani
- Dave Augustine

# 805 MHz RF test cell schematic





11/19/2002



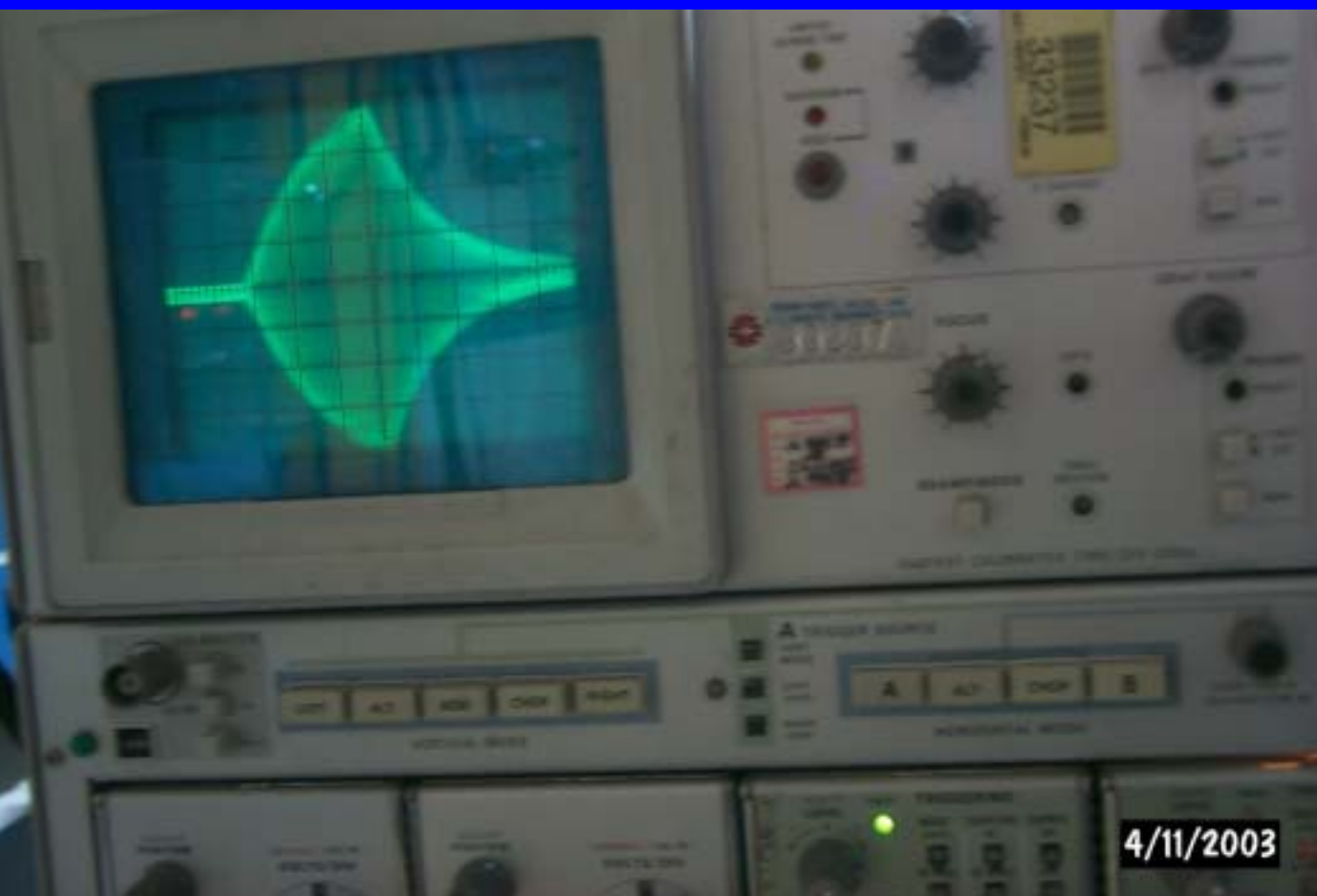


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Accelerator Physics and Technology

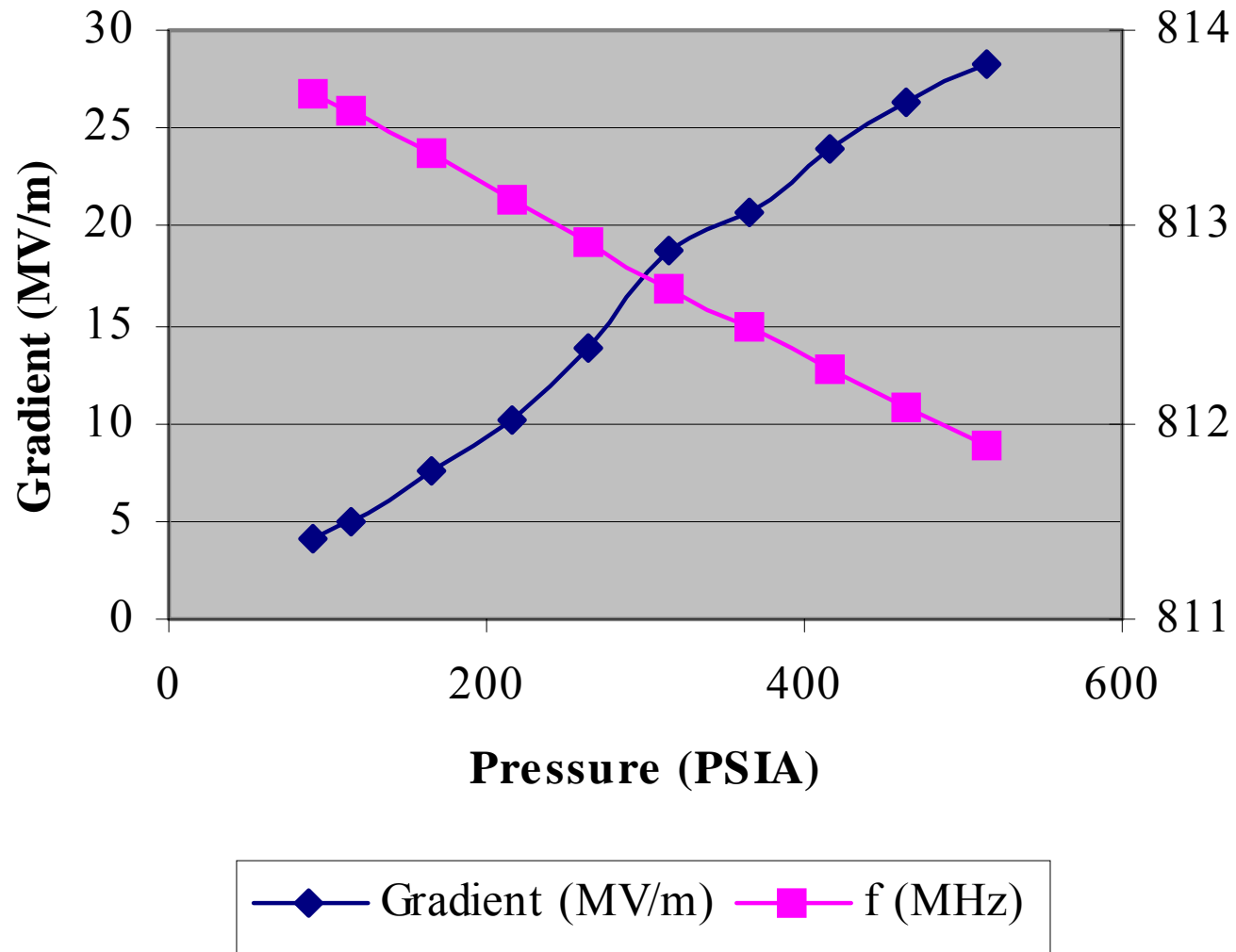
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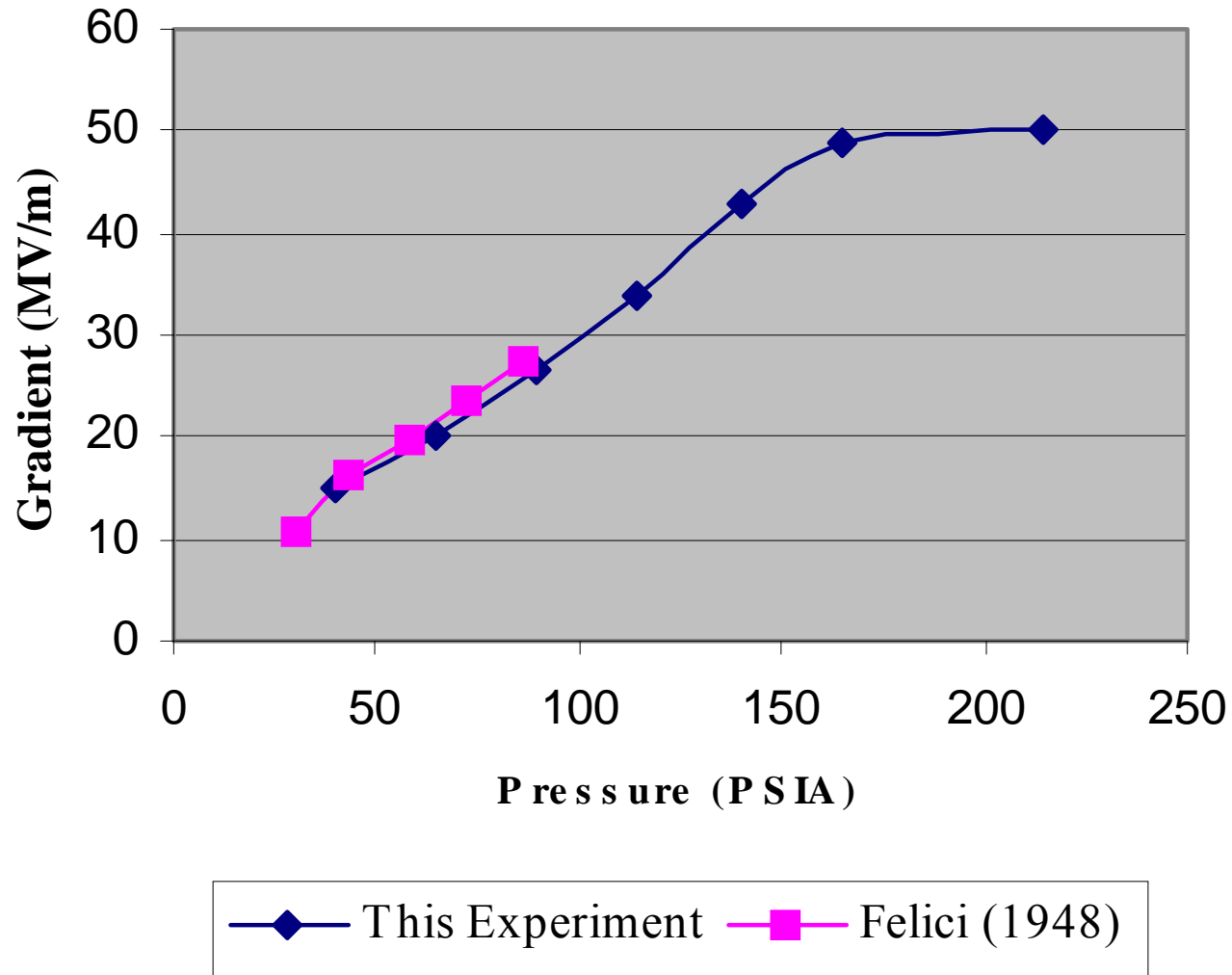




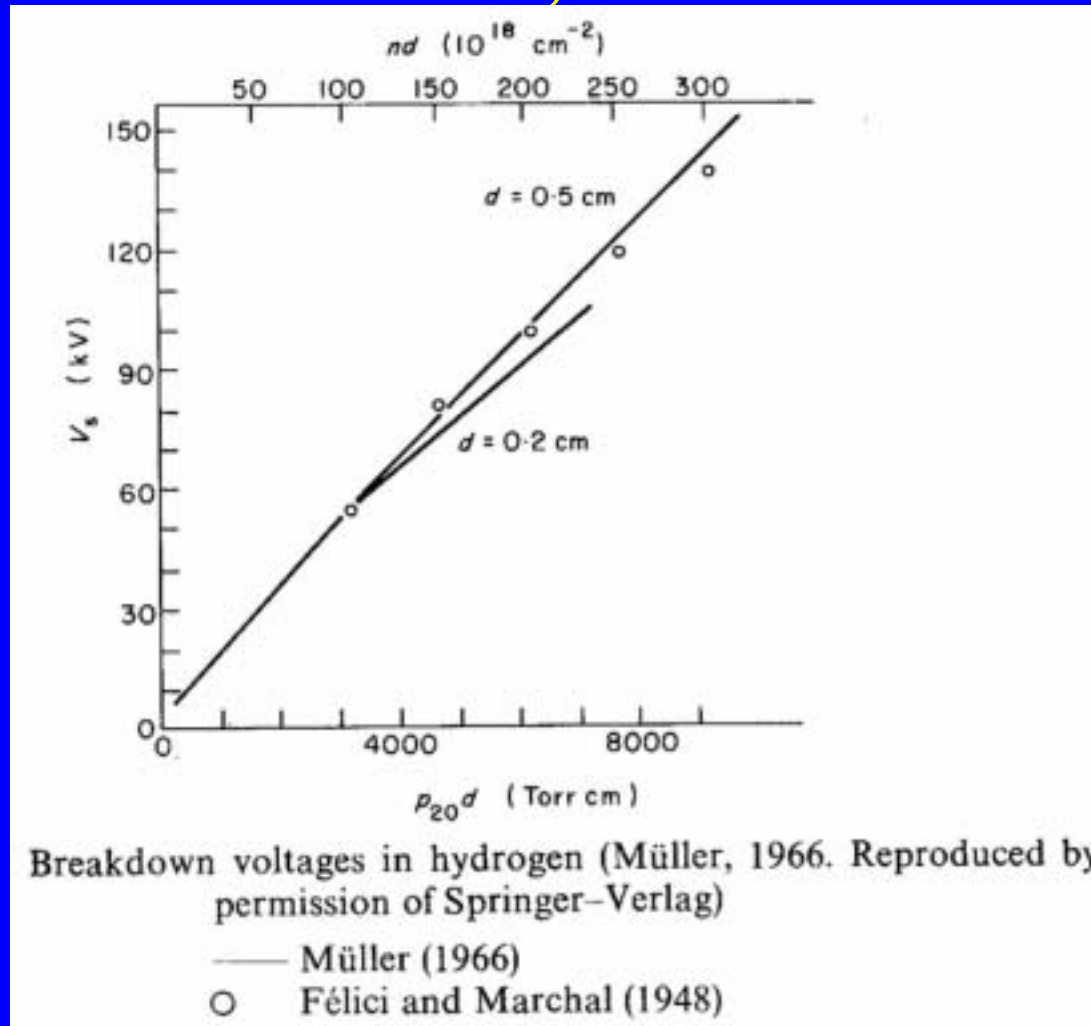
## Paschen Curve for Helium at 77 K



## Gradient vs Pressure for GH2 at 77K



# H2 DC Paschen Data existed up to $P=25$ Atm, $V=28$ MV/m







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Accelerator Physics and Technology

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# STTR Phase I & II Status

- Measured helium Paschen curve
  - Built RF test Cell
  - Achieved Phase I goal
- Measured hydrogen Paschen curve
  - Satisfied FNAL safety requirements
  - 50 MV/m at 77 K and 12 Atmospheres!
- Phase II Granted 6/23/2003!!!!
  - Study Hydrogen breakdown (B and radiation)
  - Develop cavity designs (800 & 200 MHz)



# Hopes for HP GH2 RF

- Higher gradients than with vacuum
- Less dependence on metallic surfaces
  - Dark currents, x-rays diminished
- Easier path to closed-cell design
  - Hydrogen cooling of Be windows
- Use for 6D cooling and acceleration
  - Homogeneous absorber concept

# Present Activities for HP RF Phase II project

- Study breakdown with molybdenum and other electrodes
- Redesign Test Cell for Operation in the LBL 5 T solenoid
- Ensure MUCOOL Test Area Beam Line is available in 2005



# 2003 Muons Inc. Ph I Proposals:

- Transverse Ionization Cooling (w/ FNAL)
  - MANX ion-cooling demonstration (rejected)
- RF power sources (w/ FNAL)
  - Cryogenic pulse compressors (approved)
  - Joint Venture with EM Design LLC
  - MTA facility
- 6D Cooling (w/ TJNAF) (approved)
  - Homogeneous absorber (No wedges)
  - helical dipole channel

# MANX MICE Comparison

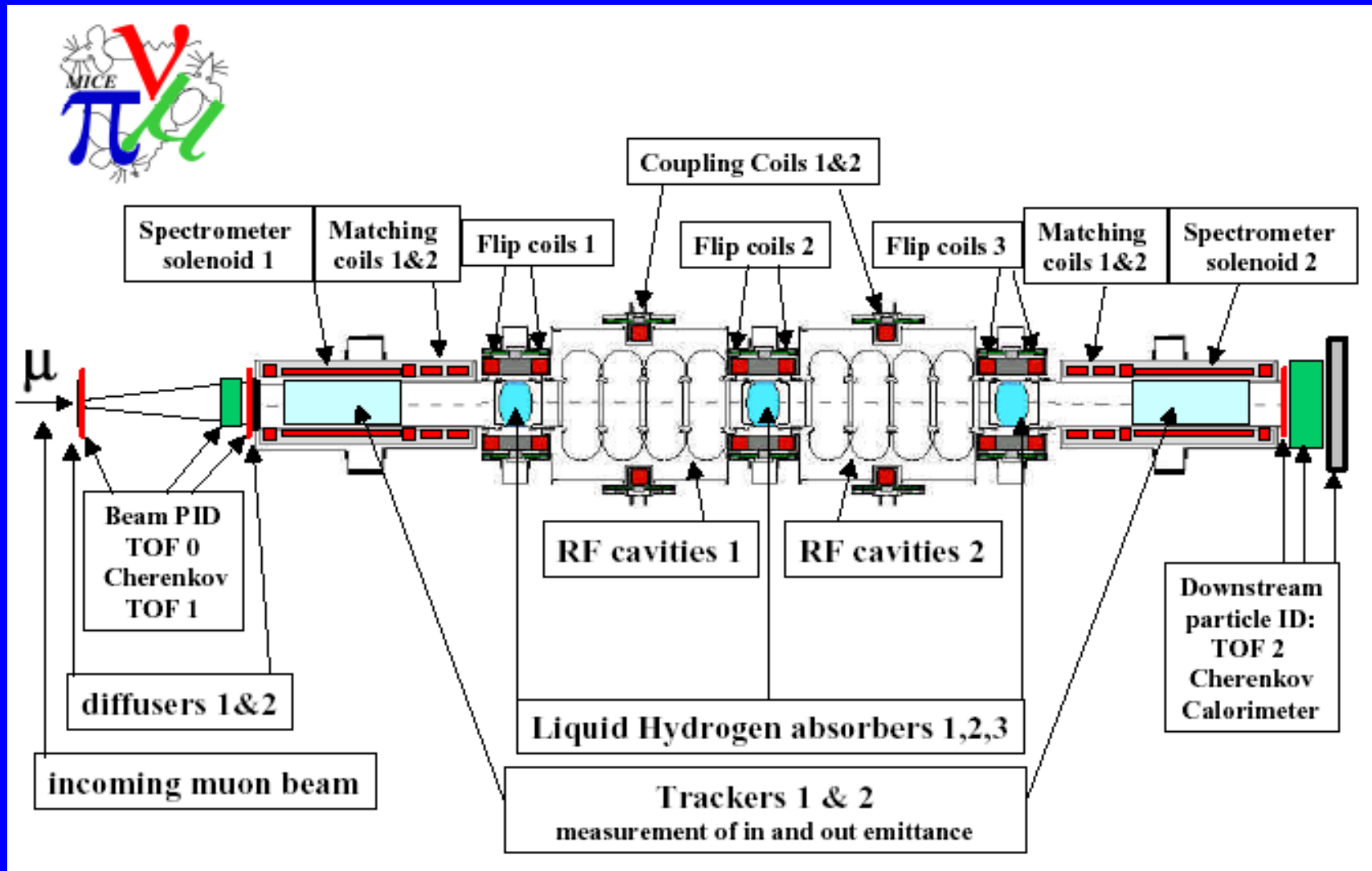
- Conventional LH2 cooling channel
  - Liquid hydrogen absorbers between RF cavities
  - Placed at low  $\beta$  locations, where solenoidal fields change direction
- Proposed GH2 cooling channel
  - Continuous dense hydrogen absorber fills RF cavities
  - Low  $\beta$  is continuous along channel

# Muon Collider And Neutrino Factory eXperiment



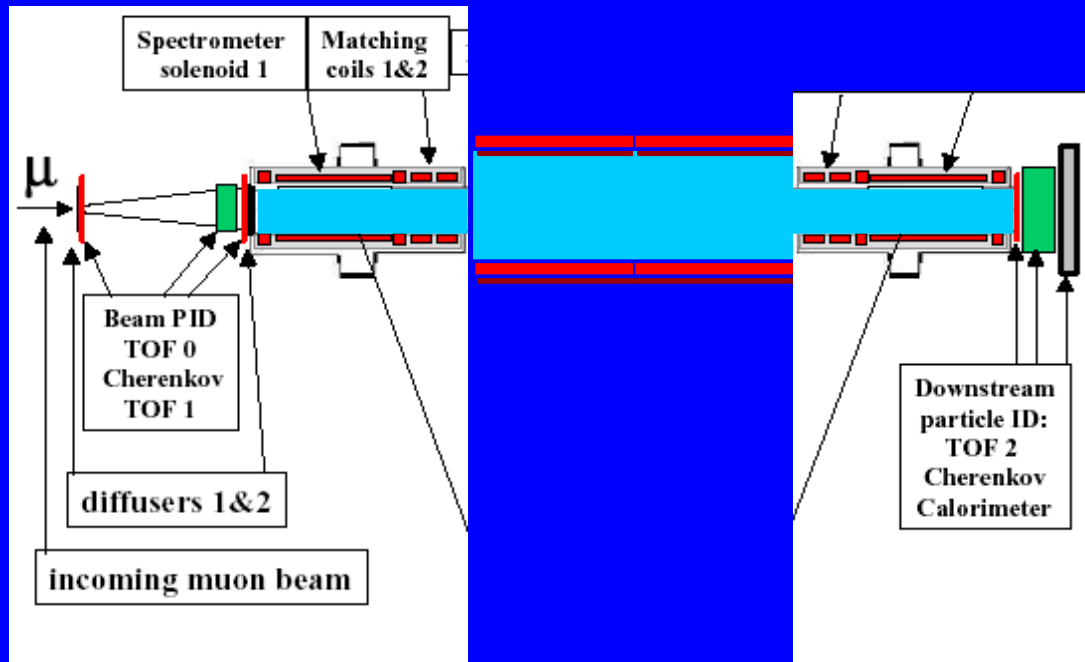
- MANX follows MICE
- Hi-Pressure GH2
- Continuous Absorber
- Continuous low- $\beta$ 
  - Single-flip Solenoids
- Internal Scifi detectors
  - Minimal scattering

# MICE



# MANX is GH2 version of MICE

MANX



# MICE changes into MANX

- Continuous GH2 replaces LH2 flasks
  - High density from P and/or T
- Opposing solenoids
  - Simple picture of “single-flip” lattice
  - Needs blackboard
- Detectors (scifi) in gas
  - No pressure windows to obscure cooling

# Cryogenic Pulse Compressors

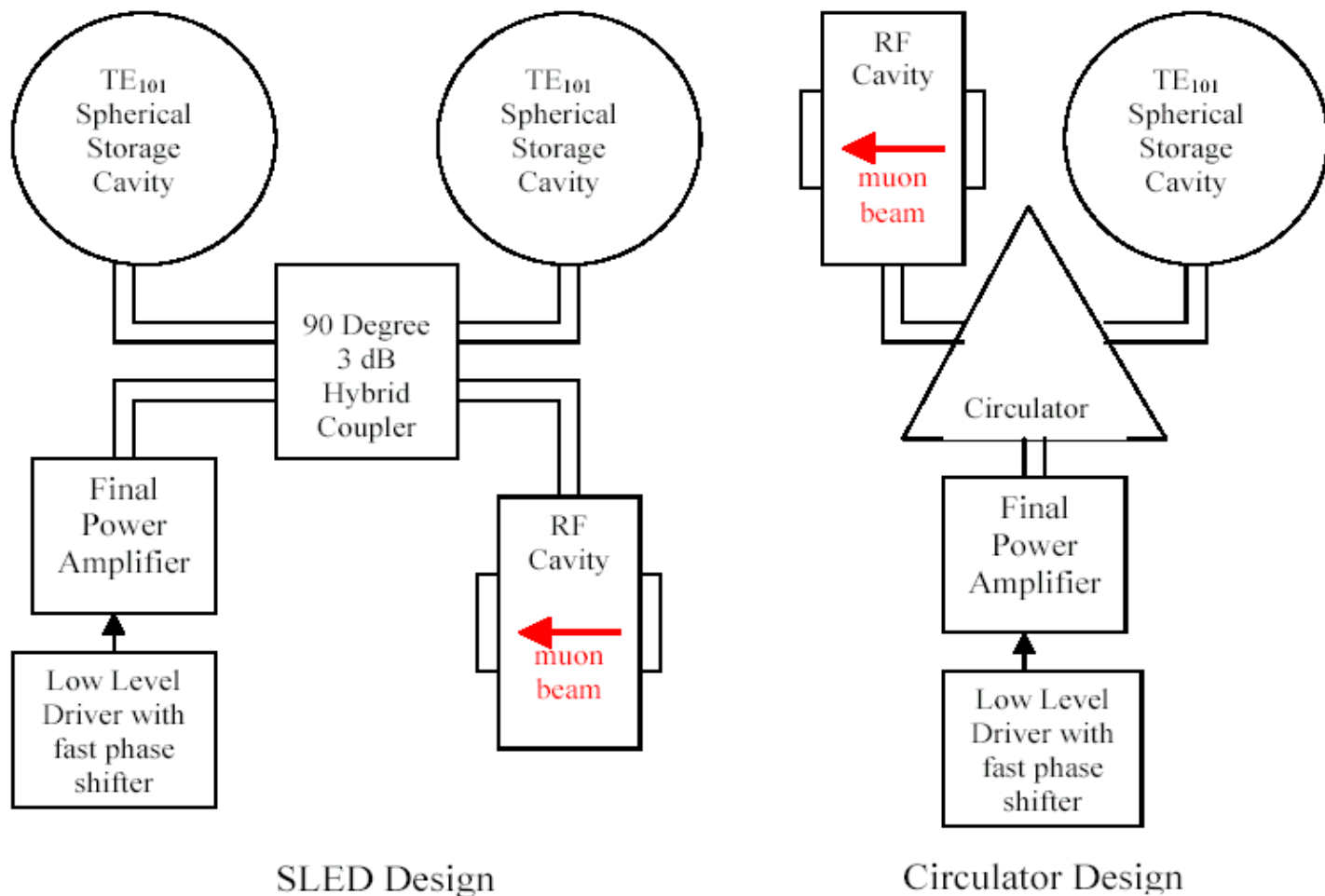


Figure 1. A comparison of the SLED and Circulator designs.

# Magic of Pulse Compression

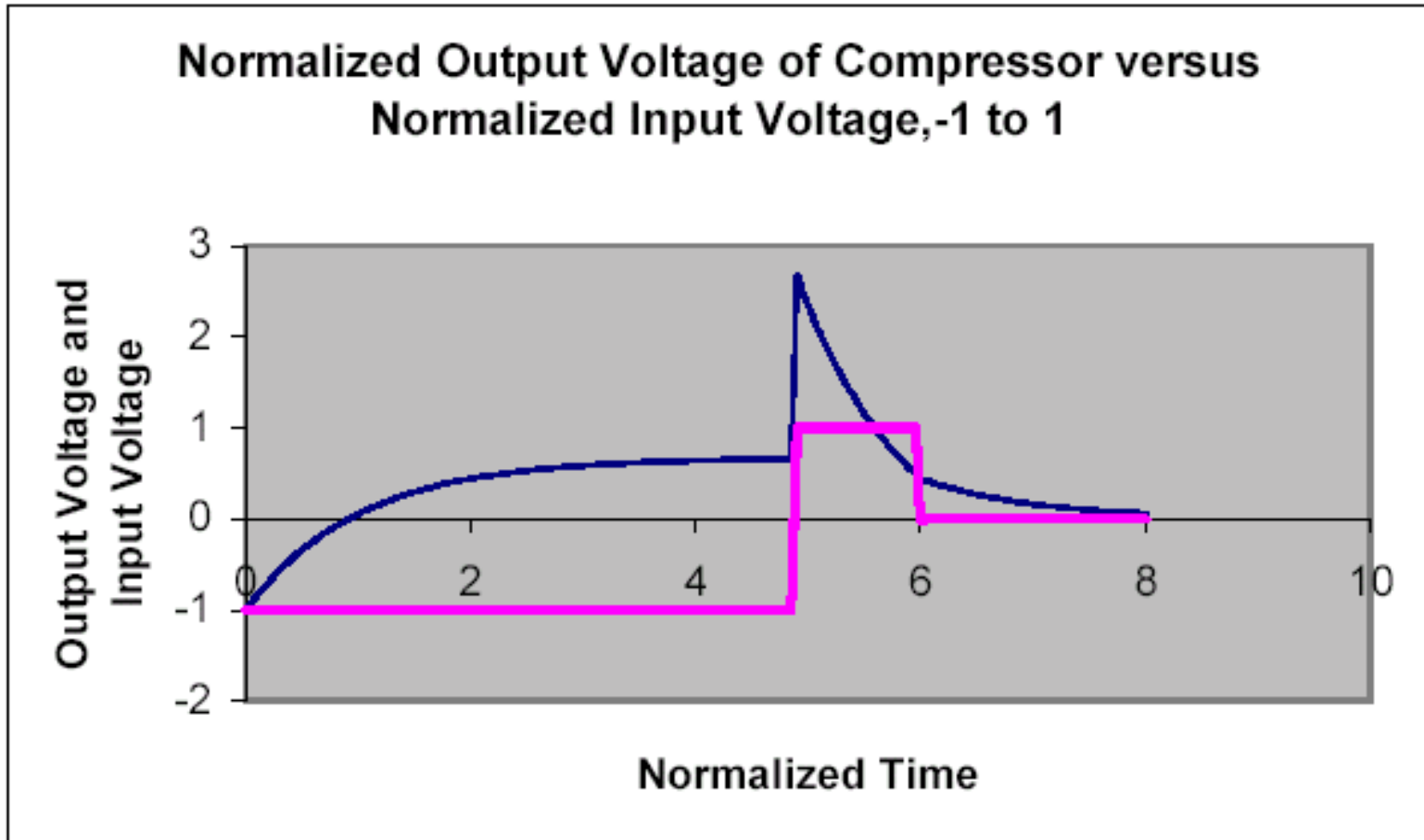


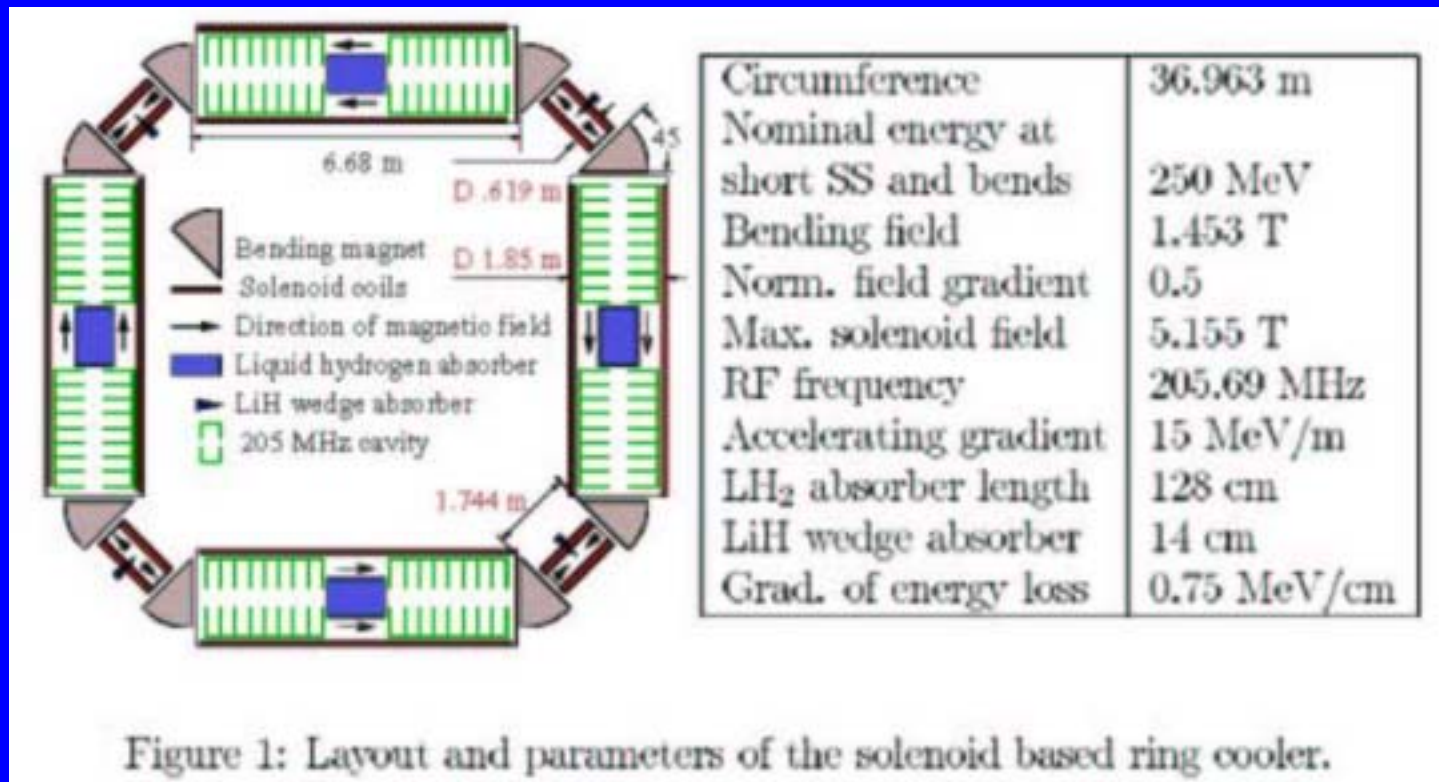
Figure 2. Input and output voltage of a compressor as a function of time.



# 6-dimensional cooling

- Essential for Muon Collider, useful for NF
- Still IC, but  $dE/dx$  depends on  $\mu$  Energy
- Ring Cooler studies in fashion
  - Generates dispersion as in a synchrotron
  - Economical: 15 turns means reused RF and absorbers
  - Problems with injection/extraction, absorber heating, RF beam loading

# Balbekov Ring Cooler



# Emittance Exchange With GH2

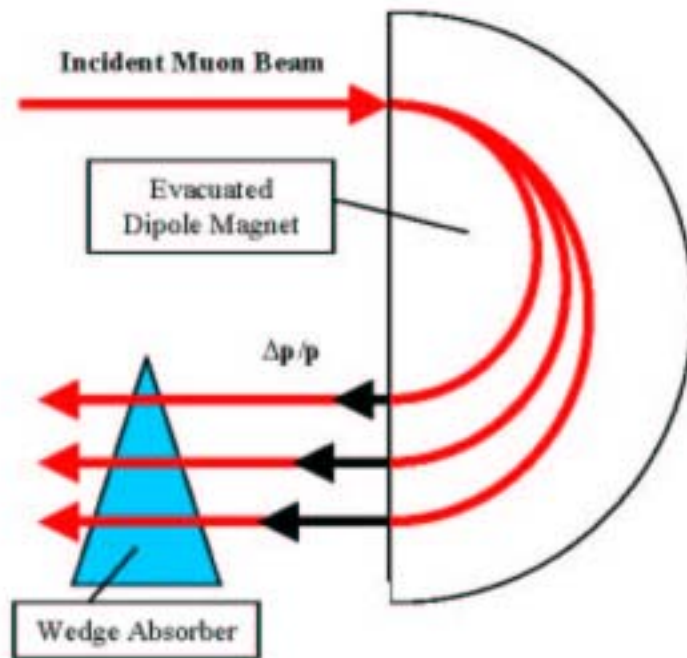


Figure 1. Use of a Wedge Absorber for Emittance Exchange

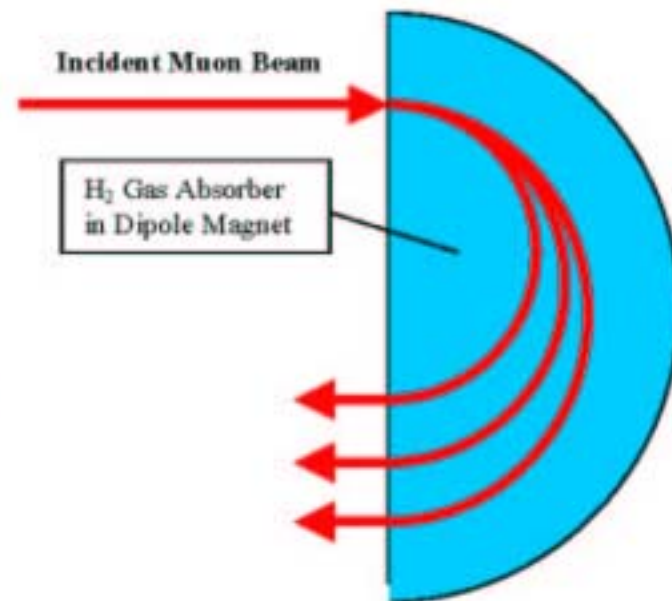
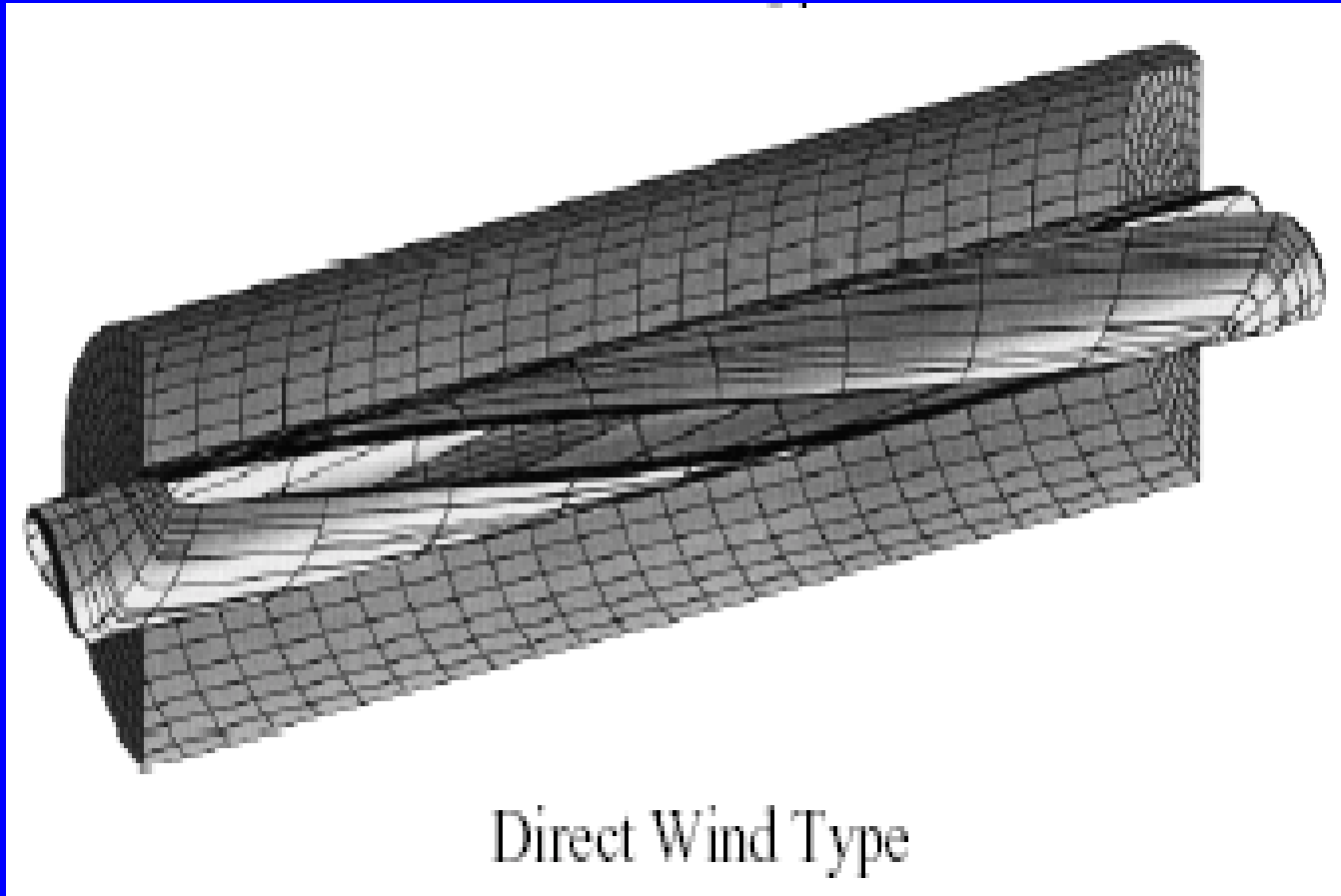


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

# Helical Dipole Magnet



# 6-d Cooling with GH2

- Derbenev channel: Solenoid plus transverse helical dipole fields
- Analytically see equal cooling decrements and  $10^6$  phase space reduction in  $\sim 150$  m channel
- Avoids ring problems
  - Injection and Extraction simpler
  - No Multi-pass Beam loading or Absorber heating
  - Can adjust channel parameters as beam cools

# Conclusions

- GH2 an enabling technology for  $\mu$  machines
  - Shorter, less-expensive, more efficient cooling
  - Less expensive acceleration for Neutrino Factory
  - 6-d Cooling makes Muon Collider possible
- SBIR/STTR funding new for basic research
  - Explicit in last solicitation
  - Muons, Inc. and IIT need physicist(s) and engineers(s).
  - CVs to [kaplan@fnal.gov](mailto:kaplan@fnal.gov) and [roljohn@aol.com](mailto:roljohn@aol.com)